JOURNAL OF THE NACAA

ISSN 2158-9429

VOLUME 17, ISSUE 1 – JUNE, 2024

Editor: Linda Chalker-Scott

Powell, J.[1]

[1]Assistant Professor (Practice), OSU Extension, Moro, Oregon, 97039

Wildfire Behavior and Establishment of Proposed Vegetative Fuel Break Plant Species in North Central Oregon

Abstract

Fuel breaks are an important tool to break up continuous fuels, such as annual grasses, to improve firefighter safety and effectiveness. Farmers across Oregon are considering fuel breaks to mitigate the risks of wildfire. Vegetative fuel breaks are fuel breaks intentionally planted with perennial vegetation with high fuel moisture and reduced flammability. Forage kochia (*Bassia prostrata*), blue flax (*Linum perenne*), and yarrow (*Achillea millefolium*) were seeded in North Central Oregon and examined as possible vegetative fuel break plant species, along with curlycup gumweed (*Grindelia squarrosa*). Fuel moisture and burn characteristics (time to ignition, duration of combustion, and flame temperature) of these species, along with cheatgrass (*Bromus tectorum*) and intermediate wheatgrass (*Thinopyrum intermedium*) were evaluated in the summer of 2022. Establishment of seeded vegetation was challenging partially due to weather variability and weed competition. Each of the four proposed fuel break plant species had significantly higher fuel moisture than cheatgrass, except for blue flax in late August. Examined burn characteristics were significantly influenced by burn date and plant species with cheatgrass showing the greatest flammability. Overall forage kochia and curlycup gumweed exhibited the greatest reduction in fire behavior. This research demonstrates that established vegetative fuel breaks can significantly alter fire behavior.

Introduction

Wildfires have increased in size and frequency across rangelands and croplands in the Intermountain region of Western North America over recent decades (Brooks et al., 2004; Shinneman et al., 2018). Large wildfires are also increasingly burning into agricultural lands. In 2018 nearly 120,000 acres of dryland wheat, pastures, and rangeland burned in North Central Oregon. Similar fires have also been burning in California, where increasingly pastures, vineyards, and other agricultural crops are being impacted by wildfires (California State Assembly Committee, 2020). The increase in the frequency and size of wildfires in agricultural areas is due to several factors, including increasing human starts, heavy continuous fuel loads of annual grasses, and changing farming practices. Annual grasses continue to spread across the Western United States, primarily cheatgrass (*Bromus tectorum*) (Balch et al., 2013; Brooks et al., 2004; Fusco et al., 2022). These invasive grasses result in a horizontally continuous and dense fuel bed that is easy to ignite and results in rapid rates of wildfire spread (Davies and Nafus, 2013). In addition, new farming practices are leaving more crop residue in the field to reduce erosion. In arid regions of the west wheat is grown in a fallow rotation system where a crop is grown every other year. In the past tillage was used during fallow years for weed control and created large areas void of fuels that easily stopped wildfires. However, now farmers have changed to no-till farming practices where residue from previous crops is left standing through the fallow year with the next crop seeded through it. This has reduced soil erosion, but has placed more fuel across the landscape to contribute to wildfire spread.

Fuel breaks can play a critical role in decreasing the size of wildfires by breaking up fuel continuity and providing firefighters with safe areas to engage wildfires where rates of fire spread and flame lengths are reduced (Maestas et al., 2016). Fuel breaks can be effective, assuming there is firefighting access to them. One study in California found that wildfires stopped at fuel breaks 46% of the time, primarily due to firefighters having access (Syphard et al., 2011). The National Wildfire Coordination Group defines fuel breaks as “natural or manmade changes in fuel characteristics which affects fire behavior so that fires burning into them can be more readily controlled.” Fuels are typically modified in fuel breaks by being removed or reduced through herbicides, mowing, or targeted grazing. Fuels can also be modified by seeding perennial vegetation to create vegetative fuel breaks.

The goal of a vegetative fuel break is to increase the proportion of plants with higher moisture content to reduce the spread of wildfire compared to more flammable and drier fuels in the surrounding landscape (Maestas et al., 2016). Fuels with lower moisture content ignite more readily as less energy is needed for ignition to occur compared to other similarly sized fuels (Thonicke et al., 2001; Chuvieco et al., 2004). Fuels with lower moisture content also contribute to wildfire spread (Thonicke et al., 2001). Plant species used in vegetative fuel breaks need to retain moisture through the fire season, be able to persist over several years, and outcompete other more flammable vegetation (Tilley and Wolf, 2020). Several plant species currently being used in the Great Basin include forage kochia (*Bassia prostrata*), crested wheatgrass (*Agropyron cristatum*), and Russian wildrye (*Psathrostachys juncea*) (Loren and Ogle, 2009; Maestas et al., 2016; Shinneman et al., 2018; Tilley and Wolf, 2020).

Forage kochia has been found to be an effective fuel break plant species in the Great Basin as it disrupts fuel continuity and maintains high moisture content through the fire season. Forage kochia is not related to annual kochia (*Bassia scoparia*), which is a noxious weed. Forage kochia is a warm season, introduced species from Eurasia originally collected from Russia in 1966 as a potential plant to suppress halogeton (*Halogeton glomeratus*) (Stevens et al., 1985). The first variety ‘Immigrant’ was officially introduced in 1984 in the United States for control of both forage and soil erosion in rangelands. In 1987 the US Congress established the Intermountain Green Stripping and Rehabilitation Research project led by BLM (Pellant, 1994). Vegetative fuels breaks were established along 451 miles because of this project, primarily using forage kochia (Pellant, 1994). Forage kochia is desirable for vegetative fuel breaks as it can persist for over ten years and keeps cheatgrass cover low (Harrison et al., 2002; Monaco et al., 2003). Previous research has found that forage kochia has 4 to 10 times the moisture content of cheatgrass in August (Pellant, 1994). Another study reported that flame lengths burning in dry grass stubble were significantly reduced as the fire spread into forage kochia, reducing flame lengths from 10 to 15 ft to 2 to 5 ft, with the fire extinguishing after burning through 2 ft of forage kochia (Monsen and Memmott, 1999).

Various perennial grasses have also been considered for use in vegetative fuel breaks as they can persist, outcompete invasive annuals, and have elevated fuel moisture compared to surrounding annuals. Intermediate wheatgrass is already well established in the Columbia Plateau and may also be suitable for use in vegetative fuel breaks. Perennial broadleaf plants other than forage kochia may also be suitable for use in vegetative fuel breaks. Yarrow (*Achillea millefolium*) is a perennial native forb that favors disturbed areas. Blue flax is also a perennial forb native to western North America and is found across diverse environments and soils (Meyer and Kitchen, 1994; Ogle et al., 2009). Curlycup gumweed (*Grindelia squarrosa*) is a short lived perennial native forb recently considered for use in vegetative fuel breaks (Tilley and Wolf, 2020). Curlycup gumweed is native to the Intermountain West and has been cultivated in the past for a possible biofuel source in Nevada (Neupane et al., 2017; Tilley et al., 2023).

Despite the multitude of plant species proposed for vegetative fuel breaks there is a lack of research quantifying their effectiveness in changing wildfire behavior. It is challenging to conduct large scale experimental burns under realistic fire conditions when burn bans are in effect. However, burn characteristics can be examined at a smaller plant scale in controlled environments. Researchers have used consistent flame sources, such as a propane burner, to quantify and compare flammability. Burn characteristics can be difficult to determine for different plants given that several external factors impact this, including temperature, humidity, and wind speed. However, at a smaller scale these added factors can be controlled and plant comparisons made.

The objective of this study was to compare fuel moisture and fire characteristics for several proposed vegetative plant species with more flammable fuels in North Central

Oregon during the peak of the fire season when relative humidity is low. We examined a total of six plant species including forage kochia, blue flax, yarrow, curlycup gumweed, intermediate wheatgrass, and cheatgrass.

Methods

Study site

Forage kochia, blue flax, and yarrow were broadcast seeded at high seeding rates of 30, 18, and 7 lbs per acre, respectively, in April 2021 in a disked agricultural field used for dryland barley hay production. Additional forage kochia was drill seeded in November 2021 at a seed rate of 6.5 lbs/acre in a different part of the same field using a JD 8200 grain drill with 7 inch spacing. Cheatgrass, intermediate wheatgrass, and curlycup gumweed were all growing next to the hay field. The field is 7.5 miles southeast of The Dalles, OR and 4 miles northwest of Dufur, OR. The site is at 1,600 ft elevation with silt and sandy loam soils and averages 12 inches of annual precipitation. Rainfall during 2021 was well below average, while in 2022 was higher than average (Figure 1.). Temperature fluctuated greatly during the spring and summer of 2022, starting below average and exceeding average temperatures during July and August (Figure 2.). Daily average relative humidity reached the lowest values of the summer during July and August of 2022 (Figure 2).

Data collection

Fuel moisture was determined by harvesting and immediately weighing plant species at five different dates (July 27, August 3, August 9, August 25, and September 1). Four 10-20 gram samples of each plant species (forage kochia, yarrow, blue flax, intermediate wheatgrass, cheatgrass, and curlycup gumweed) were collected during each sampling period. Samples were weighed again once dried to a constant weight to determine moisture content. Fuel moisture was then calculated as a percentage of dry weight. Due to an abnormally cool and wet spring measurements planned in June were delayed to late July once vegetation was done actively growing and fuels cured out enough to burn. Vegetation was intentionally sampled during July and August when relative humidity was at its lowest (Figure 2).

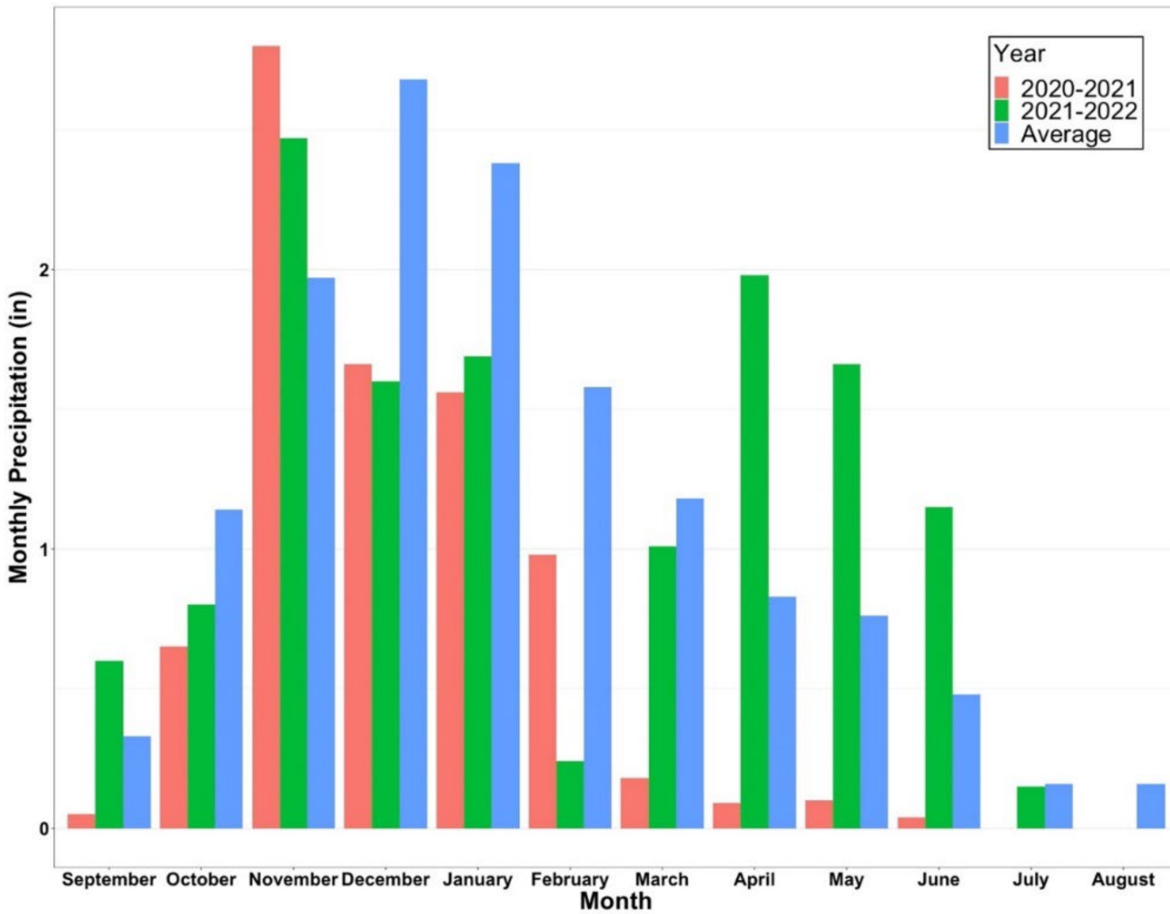

Figure 1. Monthly rainfall during each study year compared to the thirty year average in order of crop year month (September through August) as recorded at the Columbia Gorge Regional Airport in Dallesport, WA, 7.5 miles north of the study site. Weather data accessed online via NOWdata – NOAA Online Weather Data.

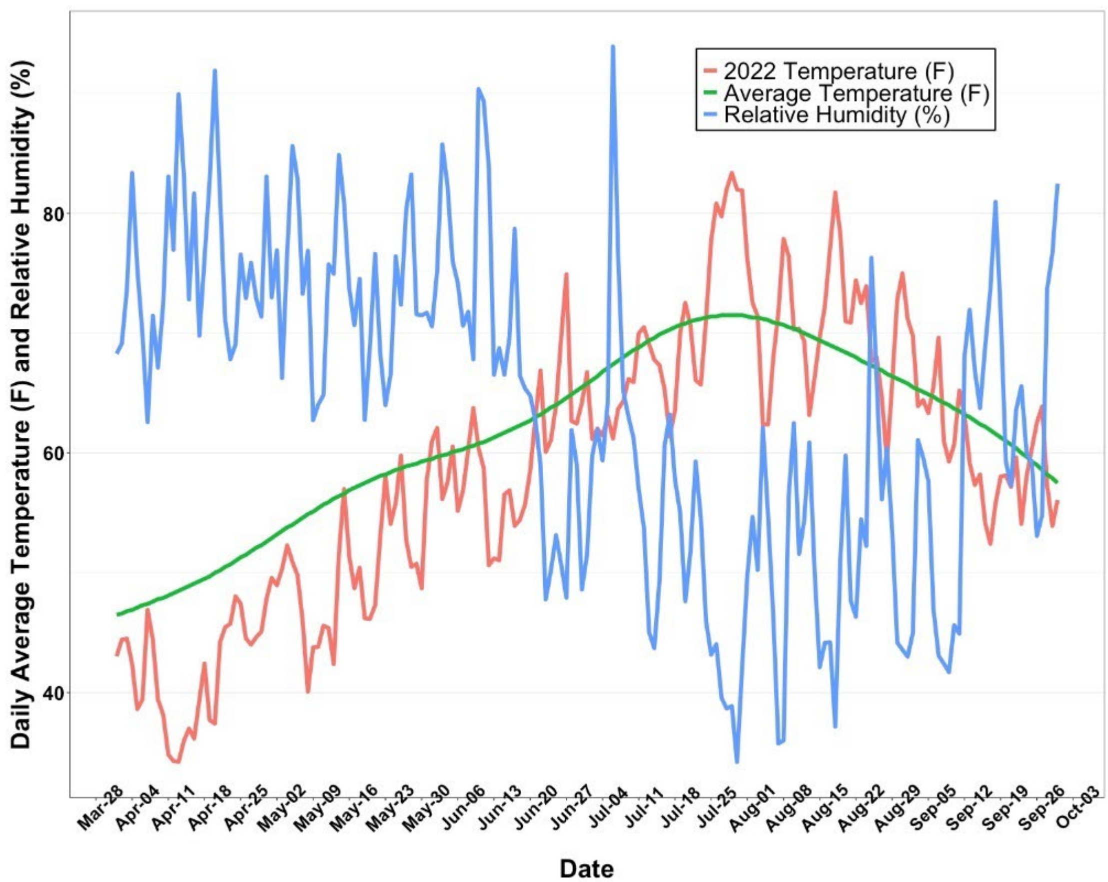

Figure 2. Daily average temperature during spring and summer of 2022 and 30 year average (F), along with daily average relative humidity (%) in 2022 for Dufur, OR reported by National Weather Service 4 miles SE of study site.

Burn tests

Burn tests followed protocols used by Tilley and Wolf (2020). Burn tests were completed on the same day that fuel moisture samples were harvested, except for August 9 when only fuel moisture was sampled. Due the lack of blue flax to harvest In September, it was not included in the last burn test. Four 12-gm samples were measured out for each plant species when collecting fuel moisture samples. Each sample was placed loosely in a 10 x 15 cm cage made of 13 mm metal mesh and put directly on a Coleman Dual Flame Powerhouse 414 stove burner using Coleman gas fuel with a flame temperature of 400 F°. A timer was used to determine time to ignition (time for the sample to sustain a flame for more than 1 second) and duration of combustion (elapsed time from ignition to extinction). In addition, peak flame temperature was determined using a Lasergrip

1022 infrared thermometer from Etekcity Corporation (Anaheim, CA) held 1.5 ft from the flames. Four different samples were burned per plant species on each burn test date. Relative humidity and temperature were monitored during burn tests using a Kestrel 5500FW Fire Weather Meter Pro. Conditions during burn tests varied throughout the summer (Table 1). The goal was to conduct burn tests during elevated fire risk in July and August when relative humidity is reduced (Figure 2).

Table 1. Relative humidity and temperature onsite during burn tests in 2022.

Burn Date	Relative Humidity (%)	Temperature (°F)
07/27/2022	39	90
08/03/2022	31	88
08/25/2022	44.6	89
09/01/2022	22	96

Statistical analysis

Analysis of variance (ANOVA) was used to determine the effect of different plant species and sampling date on fuel moisture, time to ignition, duration of combustion, and peak flame temperature. A post hoc Tukey test was used for pairwise comparisons when ANOVA results indicated a significant effect. All analyses were conducted using R (R Development Core Team, 2016). All figures show original, non-transformed data. Differences between mean values were considered significant at $p<0.05$.

Results

Forage kochia, yarrow, and blue flax that were broadcast seeded in spring 2021 initially emerged only where subsurface moisture was available due to an underground pipe leak. There was no emergence observed for forage kochia that was drill seeded in fall of 2021. Fuel moisture varied significantly with plant species and date (Figure 3). Fuel moisture was significantly higher for forage kochia, curlycup gumweed, and yarrow compared to cheatgrass from late July into early September. Curlycup gumweed started and ended significantly lower than forage kochia, but was similar during August. Fuel moisture in blue flax was significantly lower than the other three species at the end of August, but was similar in early September. Cheatgrass had significantly lower fuel moisture than other plant species, except for intermediate wheatgrass and blue flax in late August and September. Intermediate wheatgrass started off with significantly higher fuel moisture than cheatgrass, but quickly declined to similar levels.

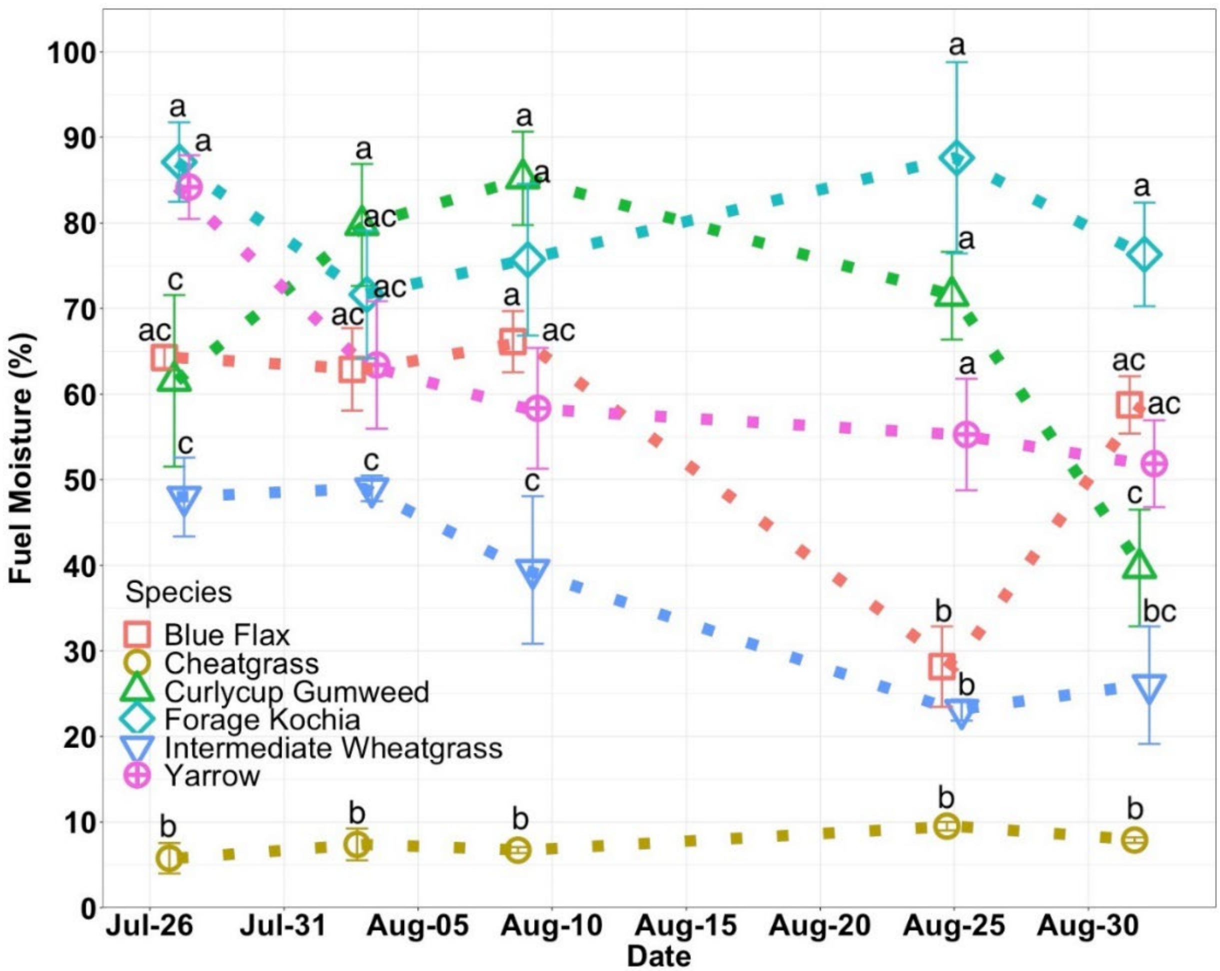

Figure 3. Average fuel moisture (%) for different plant species during the 2022 fire season from end of July through early September. Error bars represent one standard error. Different letters indicate a significant difference ($p<0.05$).

Time to ignition varied significantly with burn date and plant species ranging from a few seconds to 180 seconds (Figure 4). Both forage kochia and cheatgrass had significantly shorter times to ignition than intermediate wheatgrass during burn tests in July. However, in early August time to ignition was significantly longer for forage kochia and curlycup gumweed than cheatgrass and stayed significantly longer through August for forage kochia. Intermediate wheatgrass started in late July with significantly longer time to ignition than cheatgrass, but after the first burn date declined to similar levels. At the end of August ignition for forage kochia was significantly higher than intermediate wheatgrass. In September there were no significant differences for any of the examined plant species, though time to ignition was still higher for the four proposed vegetative fuel break species compared to intermediate wheatgrass and cheatgrass.

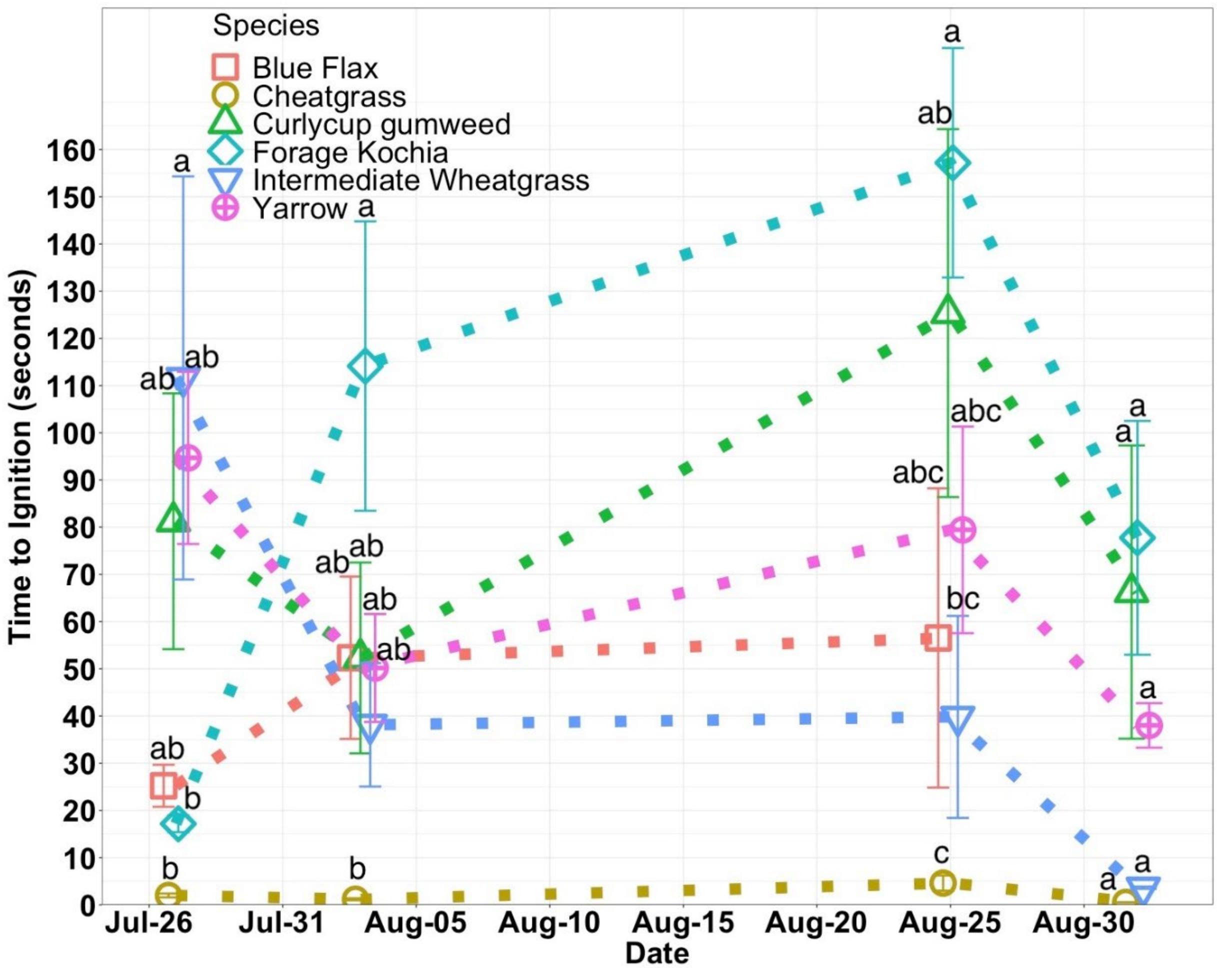

Figure 4. Time to ignition (seconds) for different plant species in 2022 from end of July through early September. Error bars represent one standard error. Different letters indicate a significant difference (p<0.05).

Duration of combustion was significantly influenced by plant species and burn date (Figure 5). Duration of combustion was significantly higher for cheatgrass at the beginning of the fire season than other plant species. In early August intermediate wheatgrass and cheatgrass burned significantly longer than other plant species. However, by the end of August duration of combustion increased for yarrow and blue flax. In September duration of combustion noticeably increased for all plant species, except for cheatgrass. Duration of combustion remained significantly lower for forage kochia and curlycup gumweed compared to yarrow and intermediate wheatgrass.

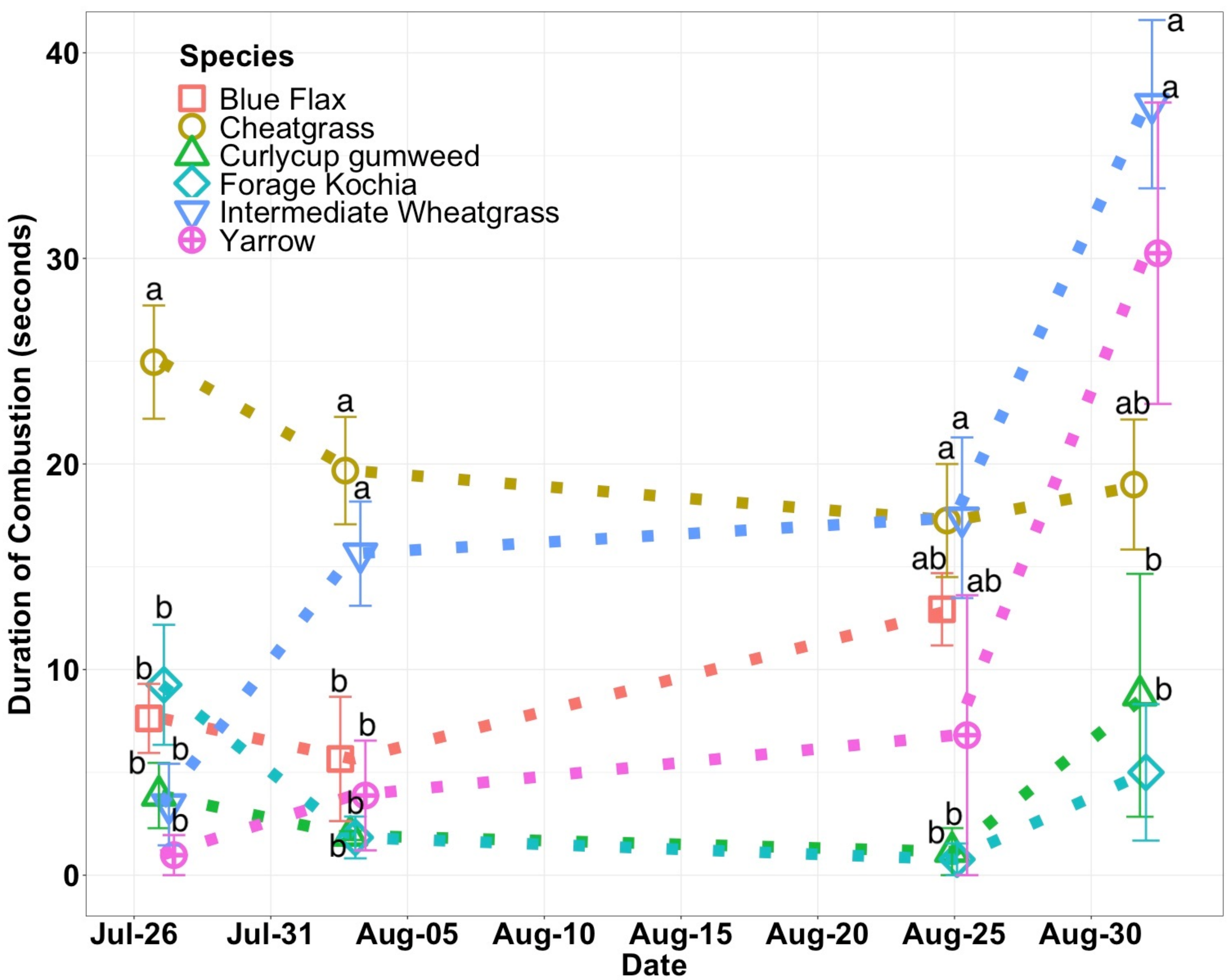

Figure 5. Duration of combustion (seconds) for different plant species in 2022 from end of July through early September. Error bars represent one standard error. Different letters indicate a significant difference (p<0.05).

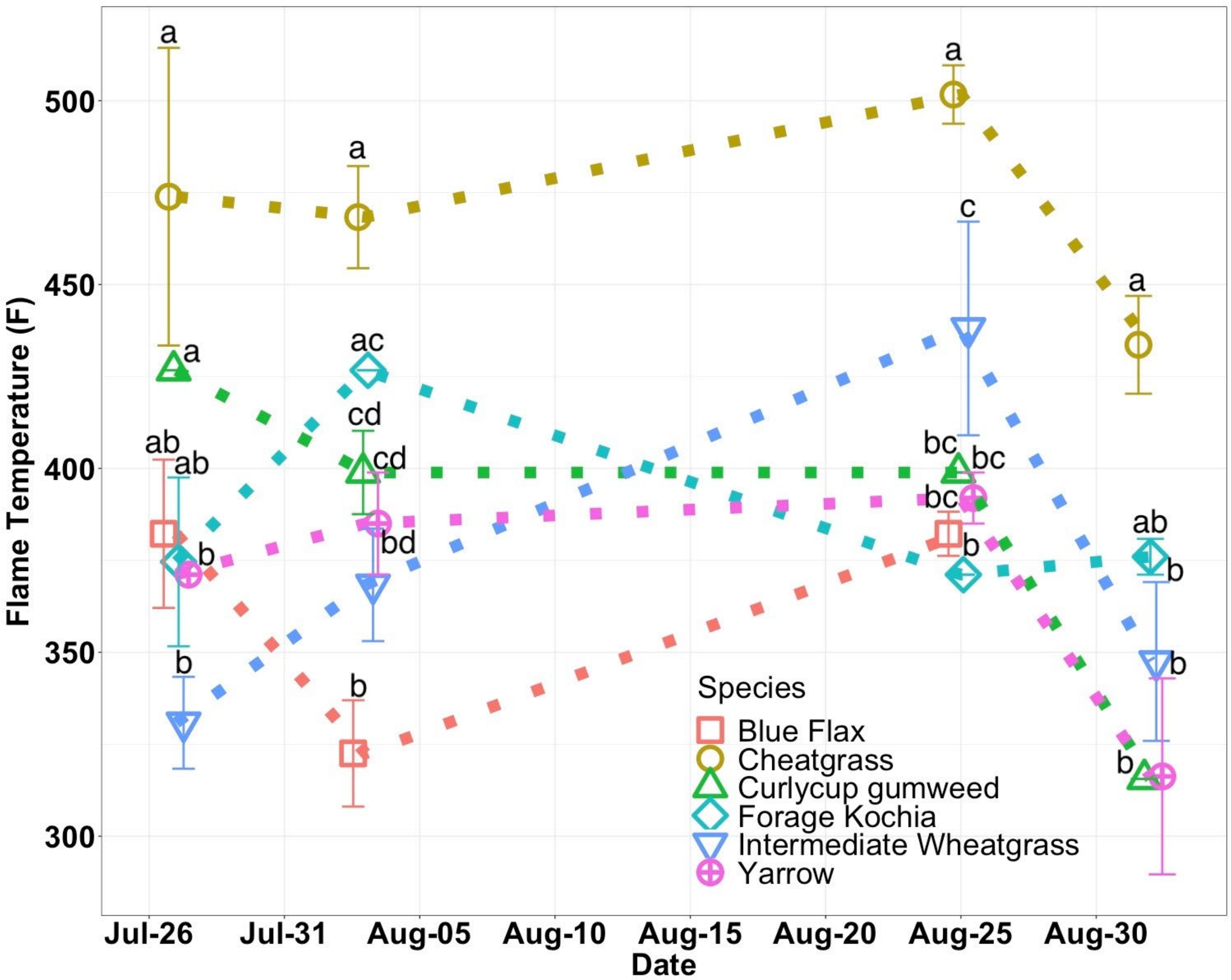

Figure 6. Flame temperature (degrees Fahrenheit) for different plant species in 2022 from end of July through early September. Error bars represent one standard error. Different letters indicate a significant difference ($p<0.05$).

Flame temperature varied significantly with plant species, but not burn date. Flame temperature showed high variability 325°F to 500°F, though was more consistent for cheatgrass than the other plant species (Figure 6). Yarrow and intermediate wheatgrass had significantly lower flame temperatures than cheatgrass and curlycup gumweed at the end of July. However, after the first burn test flame temperature stayed significantly higher for cheatgrass than for intermediate wheatgrass, blue flax, curlycup gumweed, and yarrow. Forage kochia had statistically similar flame temperatures as cheatgrass during the first two burn tests, but cooled to lower temperatures at the end of August.

Discussion

Establishment of seeded vegetation proved challenging, likely due to extreme drought in 2021 and an abnormally cool and wet spring in 2022. Broadcasted seeds in 2021 only established where there was a temporary break in an underground pipe. Perhaps if a drought had not developed in 2021, broadcast seeds would have established elsewhere in the field where subsurface irrigation was absent. In 2022 more plants did emerge that were broadcasted in 2021 due to the wet spring, however weed competition likely decreased seed emergence. Seed rates for broadcast seeding were intentionally increased to improve success, but the lack of moisture following seeding likely prevented germination regardless of seeding rate. Drill seeding rates followed NRCS recommendations for forage kochia and should have resulted in a successful population. However, the increased spring precipitation and cooler weather resulted in heavy plant competition from cool season annuals. The cooler temperatures in 2022 made it especially challenging for a warm season crop like forage kochia to emerge. Forage kochia has also been hard to establish at other sites in the region. Yarrow had better emergence and may be a better option for the climate in North Central Oregon. Curlycup gumweed is already found naturally occurring in the region and may be more suitable than an introduced warm season species like forage kochia and the other examined native forbs.

Fuel moisture monitoring did not begin until the end of July in 2022 due to the cool and wet spring that delayed the curing of most plant species examined in this study (Figure 1). Under typical spring conditions fuel moistures measured in this study would have been lower in July, but would have still reached the same levels in early September. Fuel moisture and fire behavior were only recorded into early September as farmers in the region are primarily concerned about wildfires in July and August when crops are being harvested and fire behavior is typically more intense due to lowered relative humidity. If sampling had continued into September fuel moisture would have likely stayed at similar levels and may have started increasing for forbs with increasing relative humidity and decreasing day length (Figure 2).

Fuel moisture levels declined for all species as the summer progressed, except for cheatgrass. Cheatgrass fuel moisture started low and stayed low, following the same trends observed by Tilley and Wolf (2020) during the same time period in southern Idaho. Fuel moisture in forage kochia, yarrow, and curlycup gumweed stayed significantly higher than cheatgrass through all sampling dates, except for blue flax in late August. Fuel moisture may have been lower in blue flax as growth from earlier in the growing season started to senesce. Yarrow and blue flax also had increased duration of combustion later in the summer once seed heads had formed on the plants. If blue flax or yarrow are used in fuel breaks they should be mowed at least once each year prior to fire season to prevent or remove seed set.

Fuel moisture for forage kochia ranged from 72% to 88% in this study compared to 55% to 62% as reported by Tilley and Wolf (2020). Fuel moisture was likely higher in Oregon due to fresh growth being sampled from recent plant emergence within the same year compared to older more mature plants. Fuel moisture stayed consistently high in forage kochia compared to other plant species. However, statistically both yarrow, blue flax, and curlycup gumweed had the same fuel moisture as forage kochia throughout the summer, except for blue flax at the end of August and curlycup gumweed in September. Despite curlycup gumweed having lower fuel moisture than forage kochia in September, both plants had the same burn metrics throughout the summer. Tilley and Wolf (2020) also found similar fuel moisture levels for curlycup gumweed (80% to 50%), though it declined to lower levels in this study (40%). Intermediate wheatgrass was similar in terms of fuel moisture to crested wheatgrass examined by Tilley and Wolf (2020).

Fuel moisture is a major factor in determining how easily fuels ignite (Chuvieco et al., 2004; Flannigan and Wotton, 1991). Research has found a large range of fuel moistures in herbaceous fuels at which fire is expected to extinguish from 55.5% for live fuels in Greece (Dimitrakopoulos et al., 2010) to 35% for dead grass in India (De Groot et al., 2005) and 35% for spinifex grass in Australia (Burrows et al., 1991). Values as low as 20% have also been considered for dead grasses, such as cheatgrass (Cheney et al., 1998). The plant species examined in this study appear to resist burning if fuel moistures are above 25-30%. For example, time to ignition for intermediate wheatgrass was shorter once fuel moisture dropped below 25%. Intermediate wheatgrass should not be considered for use in vegetative fuel breaks as once the fuel moisture drops later in the summer it ignites readily and burns for a long duration.

Fire weather can also alter flammability regardless of fuel moisture to an extent. Burn tests in September showed that time to ignition was lowered for all species, except for cheatgrass. Fuel moistures had also declined slightly from previous burn tests, but relative humidity during burn tests was the lowest at 22% and likely decreased the time to ignition and increased duration of combustion. Surprisingly flame temperature during the last burn date was lowered for all species, except forage kochia. Flame temperature appeared to be more closely related to unique plant characteristics than fuel moisture and did not significantly change with burn date, unlike the other burn metrics used. Flame temperatures were also quite variable for plant species, but was clear that cheatgrass burned hotter than the other examined plant species during all burn tests.

Cheatgrass exhibited high levels of flammability throughout the fire season with significantly lower fuel moisture. Flame temperatures measured were lower than reported by Tilley and Wolf (2020), likely due to the stove having a lower flame temperature in this study. Similarly, Tilley and Wolf (2020) reported shorter time to ignition and longer duration of combustion for most species compared to this study. The fine fuel structure of cheatgrass makes it easy to ignite, even when compared to fuels with similar fuel moisture levels, such as intermediate wheatgrass in September. Surprisingly forage kochia had a shorter time to ignition at the start of the fire season. Similar to cheatgrass being easy to ignite due to its high surface area, the fine hairs and high surface area of young forage kochia plants likely made it easier to ignite. During later burn tests, forage kochia was very slow to ignite as the plant became more mature and those fine hairs developed into thicker and larger leaves of the plant.

Conclusion

Forage kochia, yarrow, blue flax, and curlycup gumweed all had significantly increased fuel moisture with reduced flammability compared to cheatgrass and intermediate wheatgrass. The goal of a vegetative fuel break is to have plants that are competitive, persist, and have high fuel moisture. Unfortunately, this research does not indicate that forage kochia, yarrow, or blue flax meet all three of the preferred characteristics to be used in vegetative fuel breaks as their ability to compete and persist is questionable. As this study lasted only two years it is difficult to know how long the examined plant species would persist and due to issues with establishment lacked competitiveness. Competitiveness would have likely improved with better weed management prior to seeding through pre-emergent herbicides, tillage, or fallowing. Fuel moisture also lowered in blue flax in late August to levels similar to cheatgrass, indicating it may not be as desirable as the other examined plant species.

Curlycup gumweed was not seeded and was already well established in the area, suggesting that it can persist and outcompete other more flammable plant species. It also has increased fuel moisture with reduced flammability suggesting that it meets the three requirements to be used in vegetative fuel breaks. In addition, unlike forage kochia, curlycup gumweed is a native plant that also provides pollinator benefits. Research in Idaho has found that forage kochia can spread from seeded areas into native rangelands and should be used with caution in areas with intact native plant communities (Gray and Muir, 2013). Curlycup gumweed should be considered for further plant propagation because its use in fuel breaks has also been supported by previous research (Tilley and Wolf, 2020).

Cheatgrass in North Central Oregon is easy to ignite and once ignited burns significantly hotter and for longer than other species examined. Controlling cheatgrass should be a top priority for lowering potential fire behavior. A spark or hot ember only needs to be in cheatgrass for just a few seconds to ignite it and once ignited it burns hot and long. Vegetative or other types of fuel breaks should be prioritized in areas with annual grasses to improve firefighter safety and effectiveness.

Acknowledgements

This research would not have been possible without the cooperation of Diamond K Ranch that hosted this trial and provided the equipment and hours for field preparation and drill seeding. Thanks also to Wasco County OSU Extension Intern Keon Kiser who assisted with data collection and running burn tests. Partial funding for this project was provided by USDA/NIFA Award Number 2018-70027-28587.

Literature Cited

Balch, J.K., B.A. Bradley, C.M. D'Antonio, and J. Gómez-Dans. 2013. Introduced annual grass increases regional fire activity across the arid western USA (1980-2009). *Global Change Biology* 19(1): 173-183. https://doi.org/10.1111/gcb.12046

Brooks, M.L., C.M. D'Antonio, D.M. Richardson, J.M. DiTomaso, J.B. Grace, R.J. Hobbs, and D. Pyke. 2004. Effects of invasive alien plants on fire regimes. *BioScience* 54(7): 677-688. Retrieved from https://pubs.usgs.gov/publication/1008329

Burrows, N., Ward, B., and A. Robinson. 1991. Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. *Journal of Arid Environments* 20(2): 189-204. https://doi.org/https://doi.org/10.1016/S0140-1963(18)30708-0

California State Assembly Committee. 2020. *The Impact of Wildfires on California Agriculture Report*. 1-8. Retrieved from https://agri.assembly.ca.gov/sites/agri.assembly.ca.gov/files/The Impact of Wildfires on California Agriculture Informational Hearing Report.pdf

Cheney, N.P., J.S. Gould, and W.R. Catchpole. 1998. Prediction of fire spread in grasslands. *International Journal of Wildland Fire* 8(1): 1-13. https://doi.org/10.1071/WF9980001

Chuvieco, E., I. Aguado, and A.P. Dimitrakopoulos. 2004. Conversion of fuel moisture content values to ignition potential for integrated fire danger assessment. *Canadian Journal of Forest Research* 34(11): 2284-2293. https://doi.org/10.1139/x04-101

Davies, K.W., and A.M. Nafus. 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. *International Journal of Wildland Fire* 22(3): 353-358. https://doi.org/10.1071/WF11161

De Groot, W.J., Wardati, and Y. Wang. 2005. Calibrating the Fine Fuel Moisture Code for grass ignition potential in Sumatra, Indonesia. *International Journal of Wildland Fire* 14(2): 161-168. https://doi.org/10.1071/WF04054

Dimitrakopoulos, A. P., Mitsopoulos, I. D., and K. Gatoulas. 2010. Assessing ignition probability and moisture of extinction. *International Journal of Wildland Fire* 19: 29–34.

Flannigan, M.D., and B.M. Wotton. 1991. Lightning-ignited forest fires in northwestern Ontario. *Canadian Journal of Forest Research* 21(3): 277–287. https://doi.org/10.1139/x91-035

Fusco, E.J., J.K. Balch, A.L. Mahood, R.C. Nagy, A.D. Syphard, and B.A. Bradley. 2022. The human–grass–fire cycle: how people and invasives co-occur to drive fire regimes. *Frontiers in Ecology and the Environment* 20(2): 117-126.

Gray, E.C., and P.S. Muir. 2013. Does kochia prostrata spread from seeded sites? An evaluation from Southwestern Idaho, USA. *Rangeland Ecology and Management* 66(2): 191-203. https://doi.org/10.2111/REM-D-11-00177.1

Harrison, R.D., B.L. Waldron, K.B. Jensen, R. Page, T.A. Monaco, W.H. Horton, and A.J. Palazzo. 2002. Forage kochia helps fight range fires. *Rangelands* 24(5): 3-7. https://doi.org/10.2458/azu_rangelands_v24i5_harrison

Loren, S., and D. Ogle. 2009. *Green strips or vegetative fuel breaks*. *USDA NRCS Technical Note Plant Materials* 16: 1-16. https://www.fs.usda.gov/research/treesearch/35280

Maestas, J., M. Pellant, L. Okeson, D. Tilley, D. Havlina, T. Cracroft, and M. Williams. 2016. *Fuel Breaks to Reduce Large Wildfire Impacts in Sagebrush Ecosystems*. https://doi.org/10.13140/RG.2.2.34030.77129

Meyer, S.E., and S.G. Kitchen. 1994. Life history variation in blue flax (*Linum perenne*: Linaceae): seed germination phenology. *American Journal of Botany* 81(5): 528-535.

Monaco, T.A., B.L. Waldron, R.L. Newhall, and W.H. Horton. 2003. Re-establishing perennial vegetation in cheatgrass monocultures. *Rangelands*. https://doi.org/10.2458/azu_rangelands_v25i2_monaco

Monsen, S., and K. Memmott. 1999. Comparison of burning reliance of forage kochia, crested wheatgrass, bluebunch wheatgrass, small burnet, and western yarrow in simulated burned greenstrips, pp. 113-122. *In: Cooperative Research Studies 1989-1998. USDA Forest Service, Rocky Mountain Research*.

Neupane, B.P., D. Shintani, H. Lin, C.J. Coronella, and G.C. Miller. 2017. *Grindelia squarrosa*: a potential arid lands biofuel plant. *ACS Sustainable Chemistry and Engineering* 5(1): 995-1001. https://doi.org/10.1021/acssuschemeng.6b02315

Ogle, D., L. St John, J.S. Peterson, and D.J. Tilley. 2009. Plant guide for blue flax (*Linum perenne*) and Lewis flax (*L. lewisii*). *USDA NRCS Plant Guide* 1-4. https://plants.usda.gov/DocumentLibrary/plantguide/doc/pg_lipe2.docx

Pellant, M. 1994. History and applications of the intermountain greenstripping program, pp. 63-68. In: (S.B. Monsen and S.G. Kitchen, eds.) *Proceedings - Symposium on Ecology and Management of Annual Rangelands*. 18–21 May 1992. Boise, ID. Gen. Tech. Rep. INT-GTR-313. USDA Forest Service, Intermountain Research Station, Ogden, UT.

Shinneman, D.J., C.L. Aldridge, P.S. Coates,M.J. Germino, D.S. Pilliod, and N.M. Vaillant. 2018. A conservation paradox in the Great Basin – altering sagebrush landscapes with fuel breaks to reduce habitat loss from wildfire. *Open-File Report*.

https://doi.org/10.3133/ofr20181034

Stevens, R., K.R. Jorgensen, E.D. McArthur, and J.N. Davis. 1985. Immigrant forage kochia. *Rangelands* 7 :22-23.

Syphard, A.D., J.E. Keeley, and T.J. Brennan. 2011. Comparing the role of fuel breaks across southern California national forests. *Forest Ecology and Management* 261(11): 2038-2048. https://doi.org/https://doi.org/10.1016/j.foreco.2011.02.030

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer. 2001. The role of fire disturbance for global vegetation dynamics: coupling fire into a dynamic global vegetation model. *Global Ecology and Biogeography* 10(6): 661-677. https://doi.org/10.1046/j.1466-822X.2001.00175.x

Tilley, D., and M. Wolf. 2020. Curlycup gumweed (*Grindelia squarrosa* (Pursh) Dunal [Asteraceae]): a native forb candidate for inclusion in Great Basin greenstrips. *Native Plants Journal* 21(2): 138-149. https://doi.org/10.3368/npj.21.2.138

Tilley, D., M. Wolf, D. Jolley, and G. Hirning. 2023. Seedling emergence and seed production of curlycup gumweed. *Native Plants Journal* 23: 299-308. https://doi.org/10.3368/npj.23.3.299